Cosmic Chemistry: Cosmogony

Thought Experiments: Tracing Origins

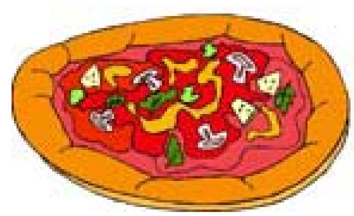
STUDENT TEXT

Cosmologists are scientists who study the structure and changes in the present universe in order to predict the future of the universe and **cosmogonists** are scientists concerned with the origin of the universe. The work of these scientists often overlaps. Observations about the structure and changes in our present universe not only allow scientists to make predictions about its future, but they also have provided clues to events that happened at the “beginning” of the chemical evolution of the cosmos.

One of the basic precepts of the standard cosmological model states that the early universe was in a state of high density and high energy. This concept was developed in much the same way that you traced back the ingredients of the pizza to their “origins.” Instead of cheese, meat, tomato sauce, and dough, cosmogonists started with what scientists have observed in the universe today:

- The rate that the universe is expanding.
- The types of structures present—like stars, galaxies, and superclusters.
- The chemical compositions of these structures.
- The evidence of energy sources present.

In addition, they applied descriptive mathematics and fundamental physical laws to develop a model of eight major “epochs” of cosmic evolution. Just as you focused on one ingredient of your pizza, we will trace **only** quarks and electrons backwards in time to discover what important role they played in those early times of high density and high energy. Keep in mind that the “universal” picture is much more complicated than the limited view that we are presenting in this short text.



How far back did you trace the ingredients in your pizza? As far back as the molecules of the three food groups—fats, carbohydrates, and protein? Or further than that—to the carbon, oxygen, hydrogen, and nitrogen atoms that make up the molecules? Did you trace the atoms of these elements back to their sources—the water, air, and soil of the Earth? If so, did you wonder how the atoms happened to be part of the Earth’s environment or how the atoms were formed in the first place?

Tracing back the matter of Earth

Most of the matter on Earth—including that in our bodies and in pizza—consists of atoms that were formed inside stars and were distributed through space in earlier **supernova** explosions. So, we are not only born of the stars but also of one of the 300 million supernovas that have exploded in our galaxy during its lifetime.

If you have completed the activities in the *Cosmic Chemistry Planetary Diversity* module, you know that the Earth is a unique planet in the solar system for a number of reasons. First, almost all of the known chemical elements have been found somewhere in the Earth’s immediate environment. Other planets may have the same wide variety but we have not yet been able to observe this in the spectra of other solar system planets. Second, many large molecules that compose living organisms have formed on our planet. Third, the temperature range of our planet is such that living organisms can exist on the surface in relative comfort. So quarks and electrons on the Earth find themselves bound up tightly in the atoms of many different chemical compounds.

Tracing back the matter of the Solar System

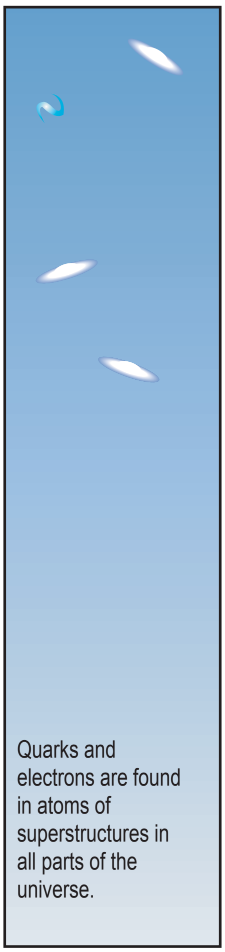
We must also remember that the Earth contains only a very minor portion of the matter in the solar system and that the solar system itself accounts for a very minute portion of the matter in the universe. Seventy-seven percent (77%) of the cosmic matter found in the massive structures of the universe—galaxies, stars, and planets—and the interstellar clouds is hydrogen; helium atoms make up 22%. Stars, such as our sun, have cores in which hydrogen nuclei are fusing into helium.

Nitrogen, oxygen, carbon, and heavier elements like iron are found in stars but these elements did not form in stars like our sun. Stars more massive than the sun can convert carbon into heavier elements such as silicon. Any elements heavier than iron can only form during a huge energy release—a supernova. A supernova explosion scatters all these elements back into the galaxy, enriching it with heavy elements that get incorporated into future generations of stars. At the end of a sun-like star's life, no supernova will occur, but the star's material will get scattered back into the galaxy by its solar wind. When our sun dies, the quarks and electrons in the solar system matter will be recycled in the formation of other suns and planets, just as they have been for billions of years.

Tracing back the matter of the superstructures

Epoch 8 - Matter condenses; Galaxies, stars, planets and life develop

3000 K to 3 K



15 billion years to 300,000 years

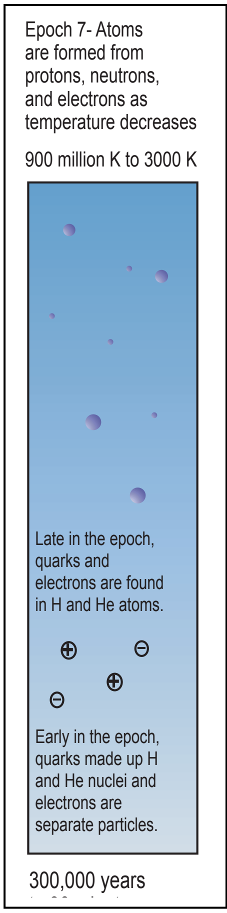
The present epoch…15 billion years, back to 300,000 years after the beginning of the universe. It is called the structural epoch because of the stars, planets, galaxies, and superstructures that now make up the universe. **Quarks are in atoms of these superstructures.**

Late in this epoch, large structures—such as stars, planets, galaxies, and clusters—were formed, so, in cosmic time, they are very recent phenomena.

At the **beginning of this epoch**, when the average temperature was about 3000 K, quarks and electrons were found in the hydrogen and helium atoms that were the major constituents of the hot gas that made up the universe.

As the temperature decreased, minor density differences in these clouds became stable regions in which matter was more concentrated. This, in turn, caused more hydrogen and helium clouds to concentrate and start rotating because of gravity, the mass attraction between the atoms. These large, rotating accumulations of hydrogen and helium were the precursors of today's galaxies.

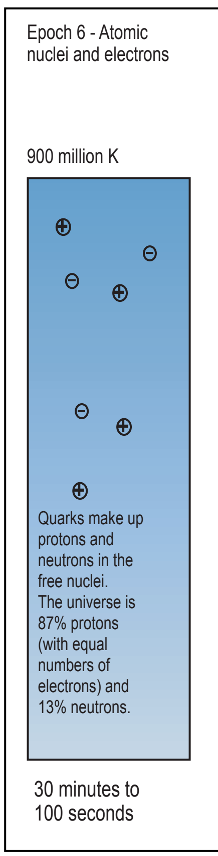
We now know that not only the clusters of galaxies and super clusters (clusters of clusters) as well as all the other elements that are present in the universe today were formed from quarks and electrons in hydrogen and helium atoms, sometime during this last cosmic epoch. But where did the hydrogen and helium atoms come from? How and when did quarks and electrons form these atoms? Let's trace them back another step in time.



The 7th epoch…300,000 years to 30 minutes—**Quarks are part of stable, neutral atoms.**

The neutral hydrogen and helium atoms that we found everywhere in the 8th epoch were formed late in this epoch as the universe expanded and cooled down from about 9×10^8 K to 3000 K.

At high temperatures at the beginning of this epoch, electrons absorbed enough energy from photons of electromagnetic radiation to overcome the positive attractive force of the nuclei that hold them in atoms. So electrons are found as separate negatively charged particles. The quarks, however, are held very tightly in positively charged hydrogen nuclei (a single proton) and helium nuclei (made of 2 protons and 2 neutrons). The ratio of hydrogen to helium in matter at the beginning of this epoch is 77% to 23%.



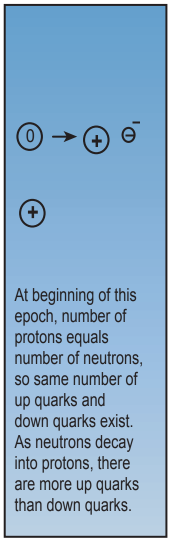
The 6th epoch…30 minutes to 100 seconds—**Quarks are found in atomic nuclei.**

Late in this epoch, the temperature is about 900 million Kelvins, but as we go farther back in time, the universe of quarks and electrons gets hotter and hotter. The ratio of hydrogen to helium atoms is 77% to 23%.

Early in the 6th epoch, about three minutes after the beginning of the universe, temperatures exceed 100 million Kelvins, and the strong forces holding two protons and two neutrons in a helium nuclei together is overcome. Deuterium nuclei, the form of hydrogen nuclei that contain one proton and one neutron, are produced. But deuterium nuclei are not very stable, so as the temperature continues to rise, these protons and neutrons are separated, so the universe contains about 87% protons and an equal number of electrons and about 13% neutrons.

Epoch 5 - Neutron decay

1 billion K



100 seconds to 10^{-3} seconds

The 5th epoch…100 seconds to 10^{-3} – neutron decay—**Quarks are found in neutrons and protons.**

Things really begin to heat up, light up and become compressed as we go backward in time!

At the end of this epoch, the universe "brew" contains more than six times the number of protons as neutrons, along with some electrons, neutrinos, and lots of photons. This also means that there are many more "up" quarks and "down" quarks.

At the beginning of this epoch, however, the universe contained the same number of protons and neutrons—and the same number of "up" quarks as "down" quarks. How did this change take place?

The temperature at the beginning of this epoch is 1 billion K. If there were equal numbers of protons and neutrons, then, at this time, there were the same amount of "up" quarks as "down" quarks. Neutrons are slightly greater in mass that protons and they are not stable at these high temperatures. The average life of a neutron is 10 minutes, so some of them decay in the 100 seconds that make up this epoch. The more stable protons take more than 1030 years to decay.

When a neutron decays, it changes into a **proton**, an **electron**, a positron, and a **neutrino**. A **neutrino** is an electrically neutral, virtually massless particle.

Neutron decay reaction:

1 no Æ 1H + oe- + oe+ + *nc*

Quark changes:

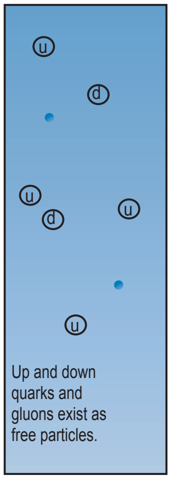
1U, 2D Æ 2U, 1D

Note what happens to the number of "up" and "down" quarks as a neutron decays. A neutron contains two "down" and one "up" quark, whereas a proton consists of two "up" quarks and one "down" quark. For every neutron decay, there is a gain of one "up" quark and a loss of one "down" quark.

The neutrinos isolate themselves and lead independent lives, occasionally colliding with electrons and other particles. Electrons and positrons immediately collide with each other and undergo matter-antimatter annihilation that results in the formation of high-energy electromagnetic photons. Comparatively few electrons survive mass extinction. The ones that did are the ones that we found in atoms in the 7th epoch.

Epoch 4 - Quarks are free

10^{15} K



10^{-3} seconds to 10^{-6} seconds

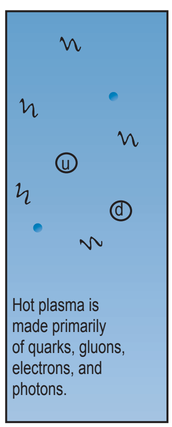
The 4th epoch…10^{-3} to 10^{-6} seconds—**Quarks are free particles**.

At this time, the universe is composed of a dense plasma that contains about 10^{27} protons and neutrons per cm^3; the average distance between their nuclear quarks is about 10^{-9} cm. In addition there are 10^{36} electrons, photons and neutrinos per cm^3.

The strong chromodynamic forces between the quarks in protons and neutrons is overcome, as temperatures increase to about 10^{15} K, releasing quarks and gluons as free particles.

Epoch 3 - Quarks are hot!

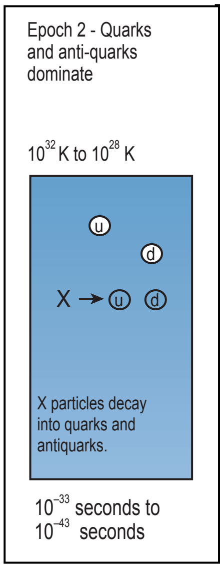
10^{28} K to 10^{14} K



10^{-6} seconds to 10^{-33} seconds

The 3rd epoch…10^{-6} to 10^{-33} seconds—**Quarks are hot!**

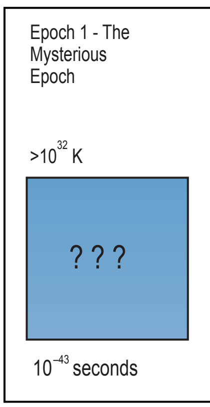
During this very short epoch, the hot plasma composed primarily of quarks, gluons, electrons, and photons cools down from 10^{28} K to about 10^{14} K.



The 2nd epoch…10^{-33} to 10^{-43} seconds--**Quarks and antiquarks are dominant**.

The temperature of the primal stew made up of the hot plasma of quarks, gluons, electrons, and photons and ***X* particle**, (and all their corresponding antiparticles) drops from 10^{32} K to 10^{28} K during the 10^{-10} seconds of this 2nd epoch.

What were these *X* particles? They are thought to be particles that decay into more quarks and antiquarks as the temperature significantly decreases, as it may have during the 2nd epoch. These quarks and antiquarks annihilated each other immediately upon contact, produced either two photons or an electron-positron pair, which, in turn, triggered further matter-antimatter destruction. But, more importantly, this *X* particle decay resulted in a **very slight excess** of quarks to antiquarks. The excess is only one out of billion quarks, but this is a significant excess.



The 1st epoch…the first 10^{-43} seconds--**The Mysterious Epoch.**

The details are not known. The events that happened here have been called the "Big Bang," but there are differing opinions as to what really occurred during this brief time in history. We are quite confident, however, that the temperature of the high-energy, very compact and condensed universe in this 1st epoch was above 10^{32} K.

Limitations of our search

Just as you focused on the one pizza ingredient that you traced back to its "beginning" to the exclusion of all other matter around it, we did much the same thing as we looked for the "beginning" of quarks and electrons. We limited ourselves to one model of the early universe, because it is most closely correlates some of the basic precepts of the standard cosmological model with the fundamental particles—quarks and electrons. There are other models that may be just as valid as this one, but this is the theory currently accepted by the scientific community.

From its "genesis," the universe was much more complicated and many more things were happening than what we have described in this short text. There were some great matter-antimatter annihilations taking place that we only briefly mentioned and there were many other small, but significant, matter particles present that we ignored because they did not interact with quarks.

Probably one of the most significant results of tracing the history of quarks in the universe is that we found that their ultimate origin is uncertain. But cosmogonists are still seeking answers to questions about "the beginning," using giant particle colliders and studying the solar wind particles collected by the Genesis spacecraft. Keep tuned to the Genesis Web site for the newest information.